NATO ARW, Kyiv, Sept. 07–13 2003

The Main Tendencies in Elaboration of Materials with High Specific Strength

Professor S. Firstov

I.M. Frantcevych Institute for Problems of Materials Sciences

Kyiv, Ukraine

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
18 MAR 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	
The Main Tendencies in Elaboration of Materials with High Specific Strength	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **I.M. Frantcevych Institute for Problems of Materials Sciences Kyiv, Ukraine**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001672., The original document contains color images.

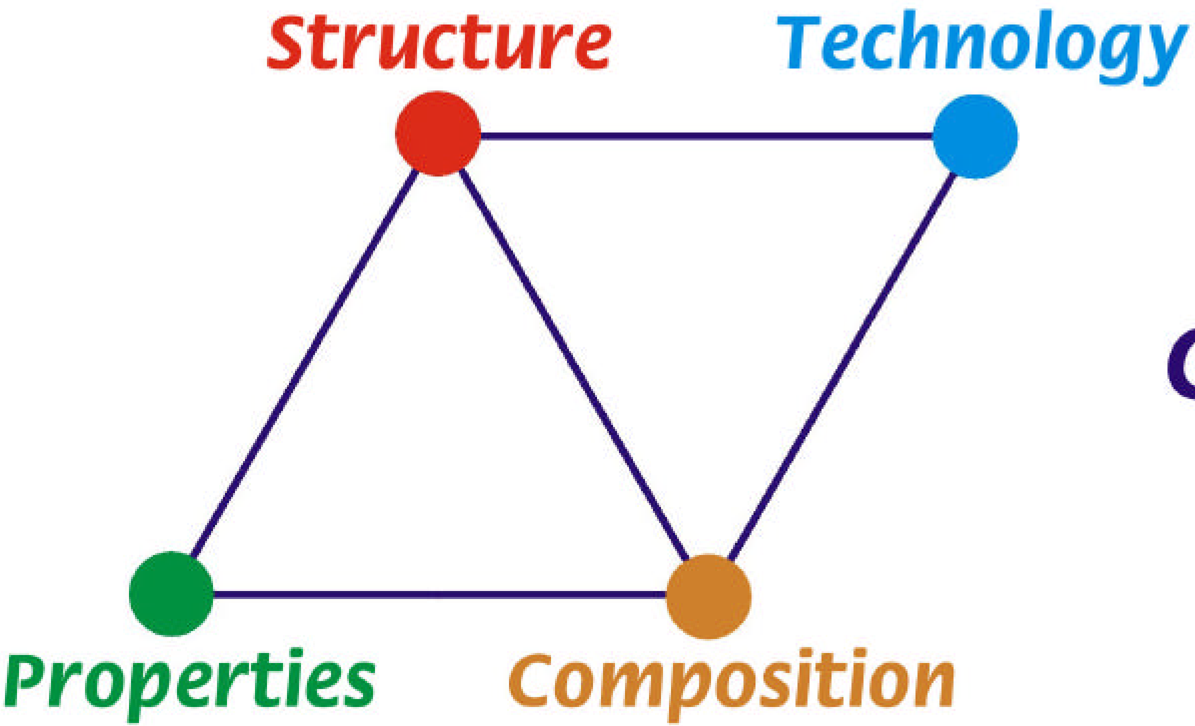
14. ABSTRACT

15. SUBJECT TERMS

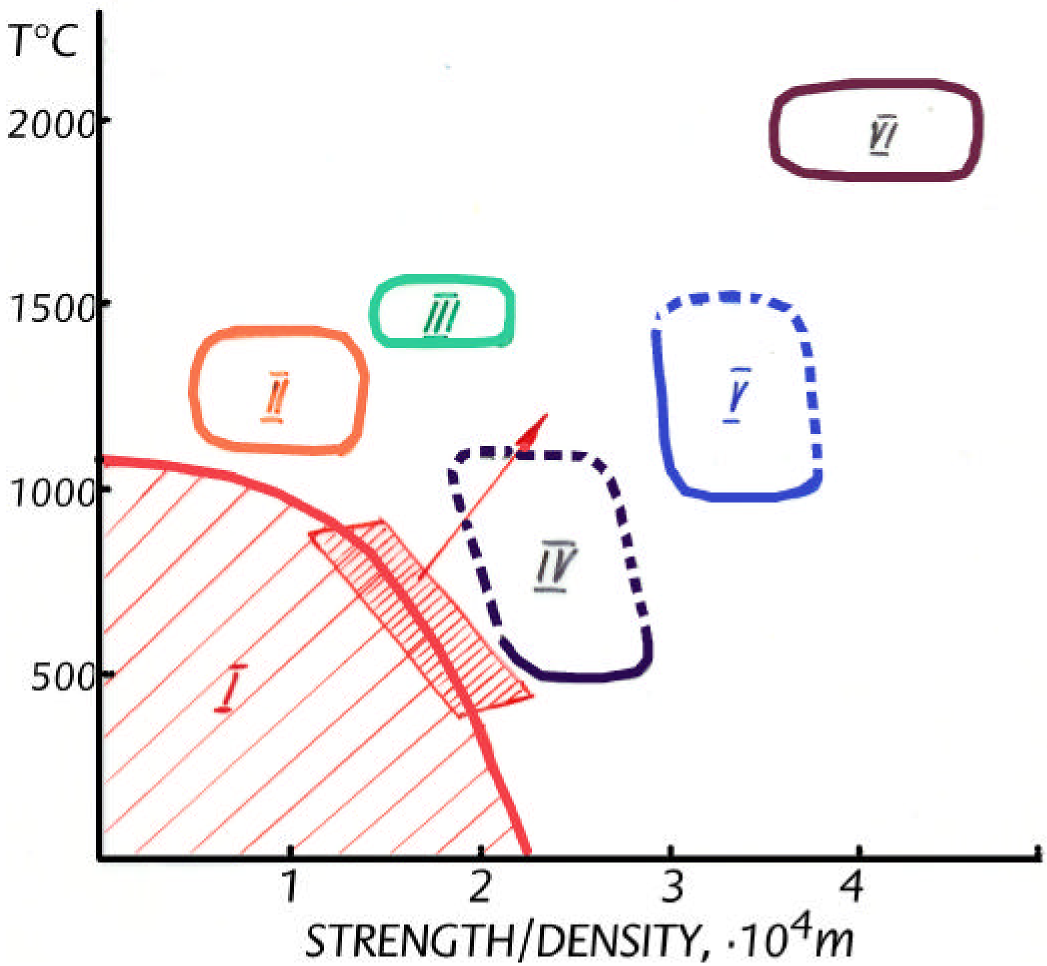
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
NATO/unclassified	**unclassified**	**unclassified**	**UU**	**40**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Introduction
- Nanostructured materials
- Ti-Si-X and Ti -B-X systems as the base for elaboration of new in situ composites
- Conclusions



Cost ?



I - Conventional materials, Ti and superalloys

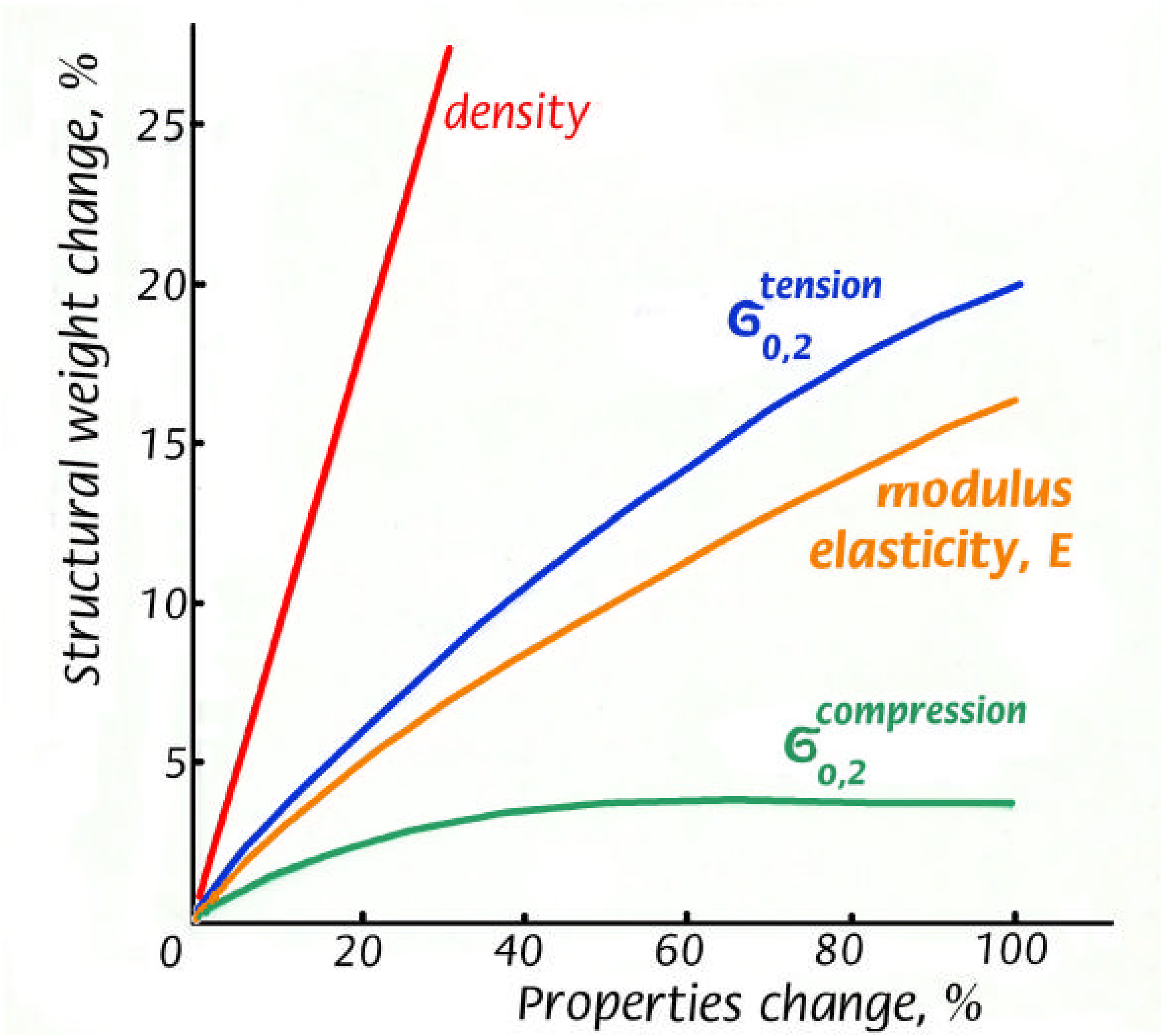
II – Metal matrix composites

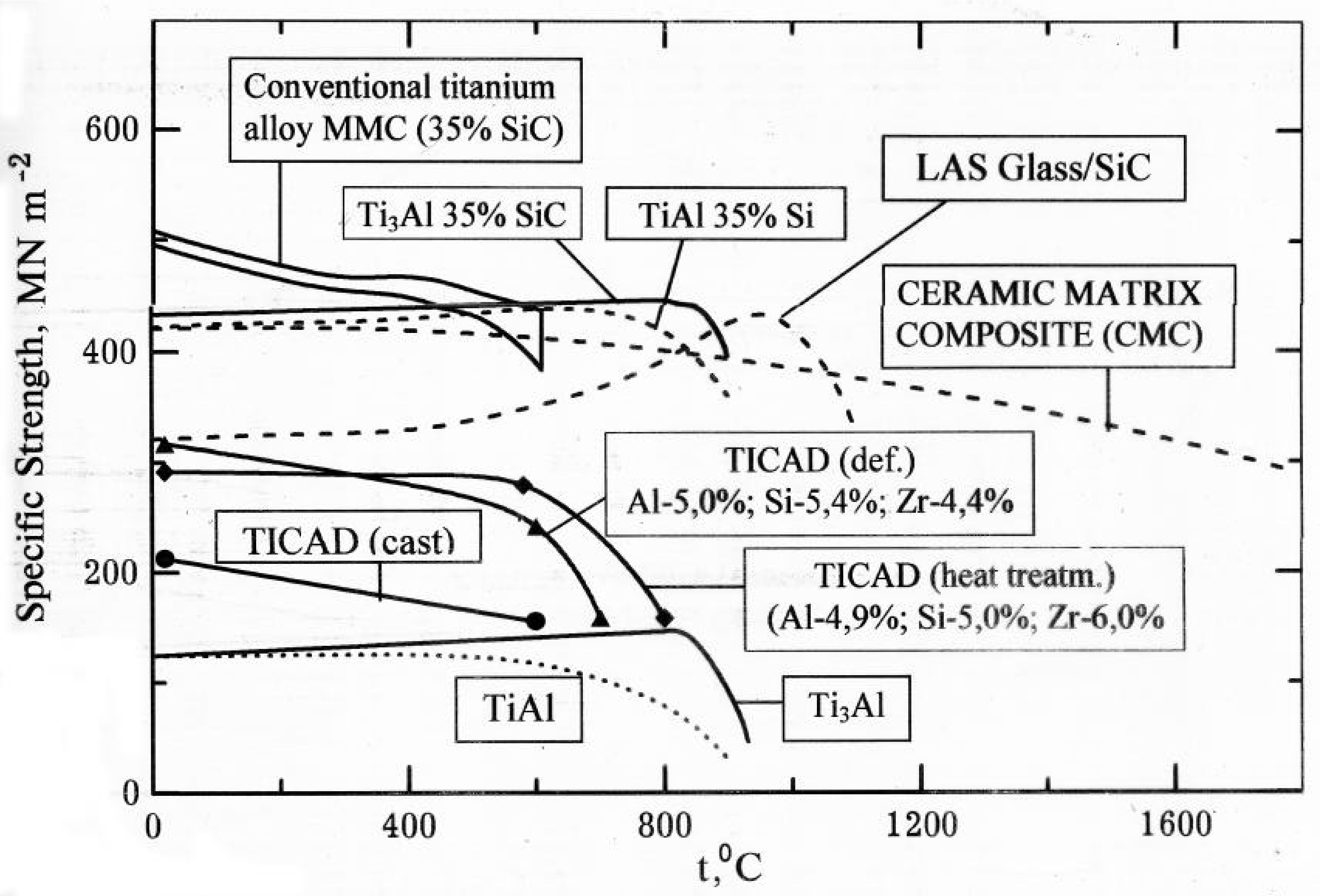
III – Ceramics

IV – Intremetallic composites and intermetallic

V – Ceramic composites

VI – Carbon / carbon composites


Structural weight change, %
25
20
15
10
5
0
20
40
60
80
100
Properties change, %
density
tension
0,2
modulus
elasticity, E
compression
0,2



Specific Strength, MN m^{-2}
600
400
200
0
0
400
800
1200
1600
t,^{0}C
Conventional titanium alloy MMC (35% SiC)
Ti_3Al 35% SiC
TiAl 35% Si
LAS Glass/SiC
CERAMIC MATRIX COMPOSITE (CMC)
TICAD (def.)
Al-5,0%; Si-5,4%; Zr-4,4%
TICAD (cast)
TICAD (heat treatm.)
(Al-4,9%; Si-5,0%; Zr-6,0%
TiAl
Ti_3Al

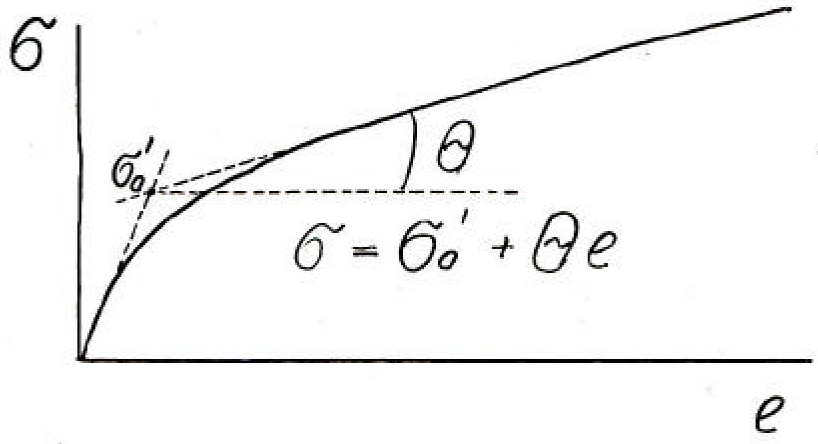
PART 1

Nanostructured materials produced via severe plastic deformation and other technologies

Unusual properties of nanomaterials

1. Reduced density (up to 10%)
2. 2. Reduced modulus of elasticity (up to 10%) and Debye temperature (in the case iron 240K instead 476K)
3. 3. Some severe deformed metals demonstrate good RT plasticity (Ti, Al, Cu)
4. 4. Increased solubility of interstitial elements
5. (Carbon in Iron up to 1.2% instead 0.06% at RT)

DEFORMATION HARDENING



$$s = s'_S + \Theta e$$

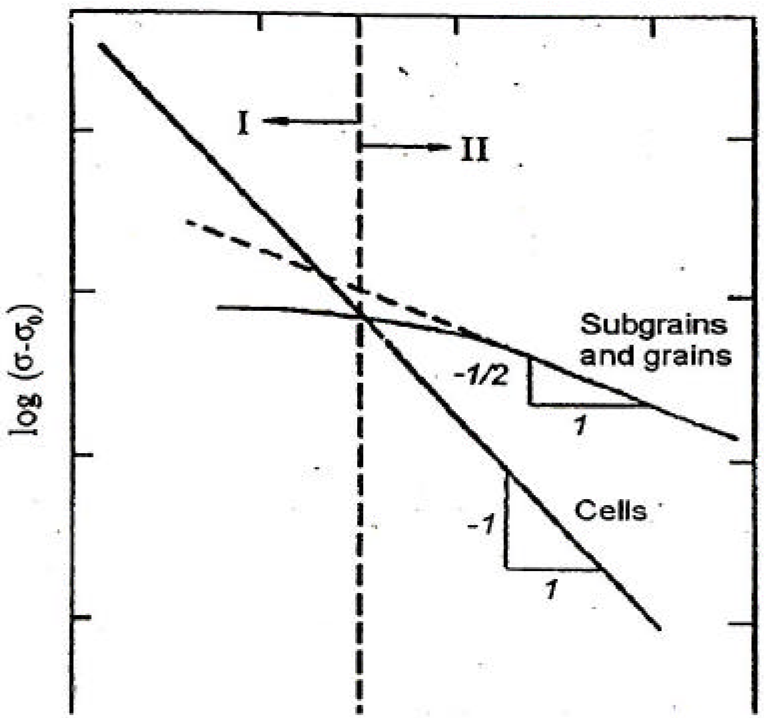
$$s = s_0 + kd^{-1}$$

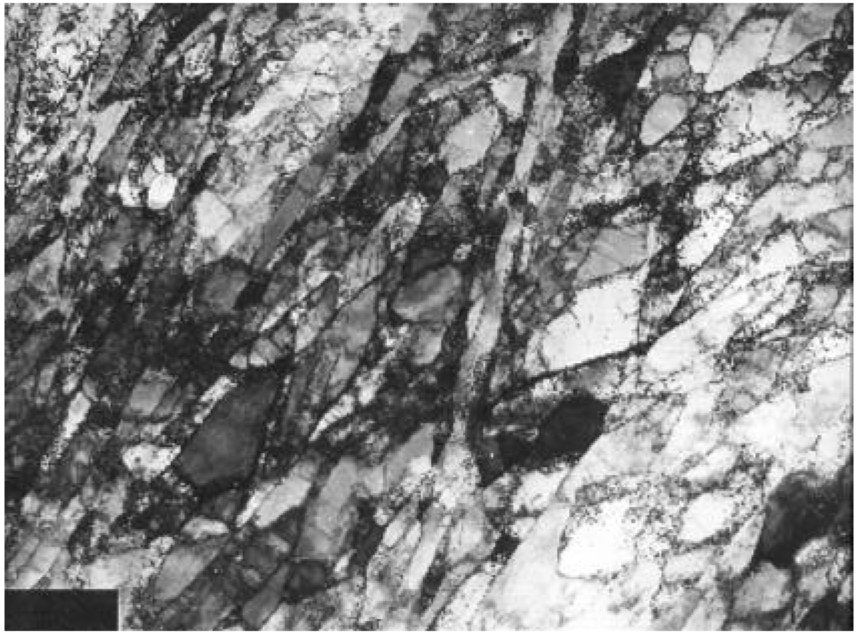
$$d(e) = \frac{k}{\Delta s + \Theta e} = \frac{d_0}{1 + ae}$$

Material	σ_{theor} **, MPa**	e_{ult}	d_{ult} **, ì m**
Mo	11000	25	0.02
Fe	7130	40	0.02

MECHANISMS OF STRAIN HARDENING

(*Thompson A.W.*)





Efficiency of various mechanisms of hardening dependence of substructural elements (schematic diagram):
I – hardening cells;
II – hardening by grains prevails.

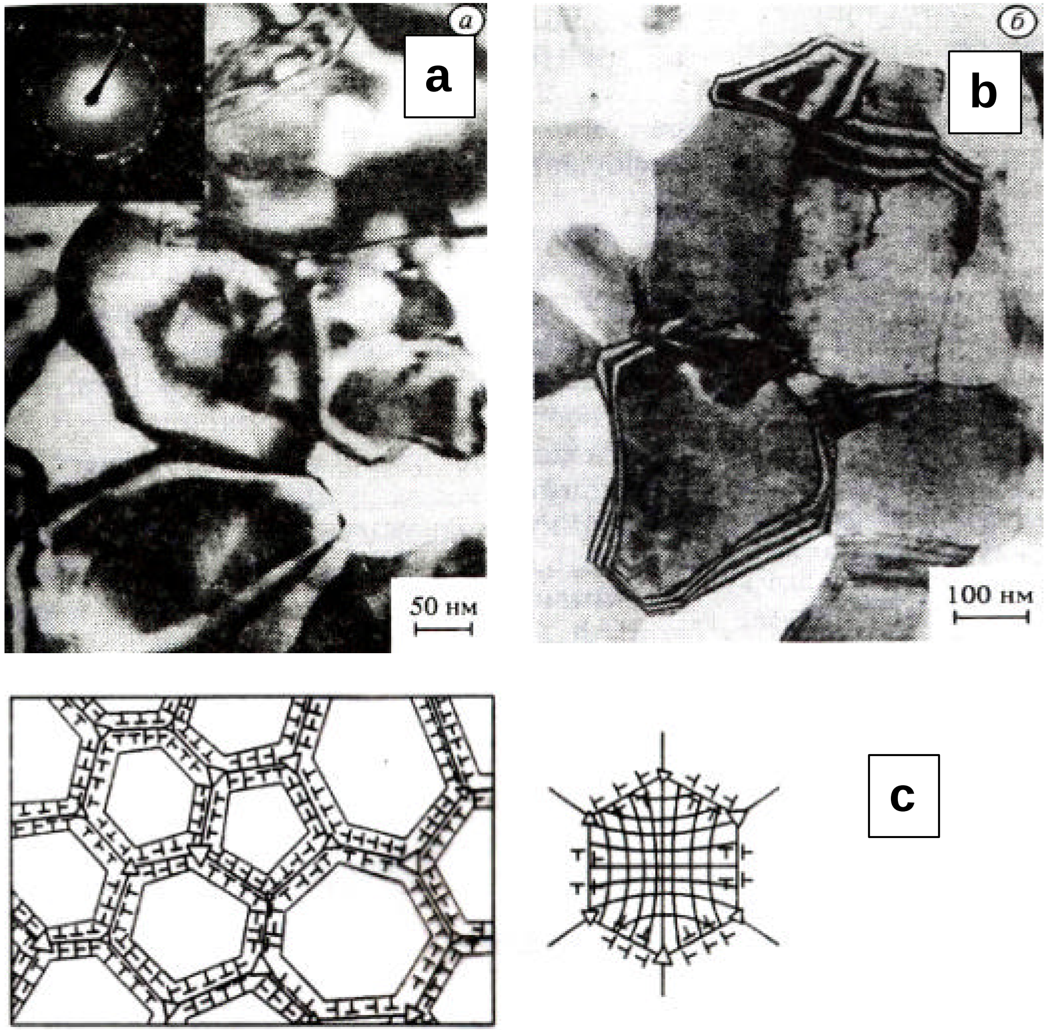
The critical sizes of structural elements (grains)

$$\Delta\sigma \sim d^{-0.5} \text{ ® } \Delta\sigma \sim d^{-1}$$

$$0.4\ \mu m \leq d \leq 1\ \mu m$$

$$\sigma = \alpha Gb/L \rightarrow \sigma_{theor}$$

$$d \leq 0.02\ \mu m$$



Grain boundary in the heavily deformed Al-4%Cu-0.5%Zr alloy:

(a) after deformation at e=7 and T=20 ^{0}C;
(b) after additional annealing at 160 ^{0}C for 1 h;
(c) schematic illustration of the GB in nanostructured state

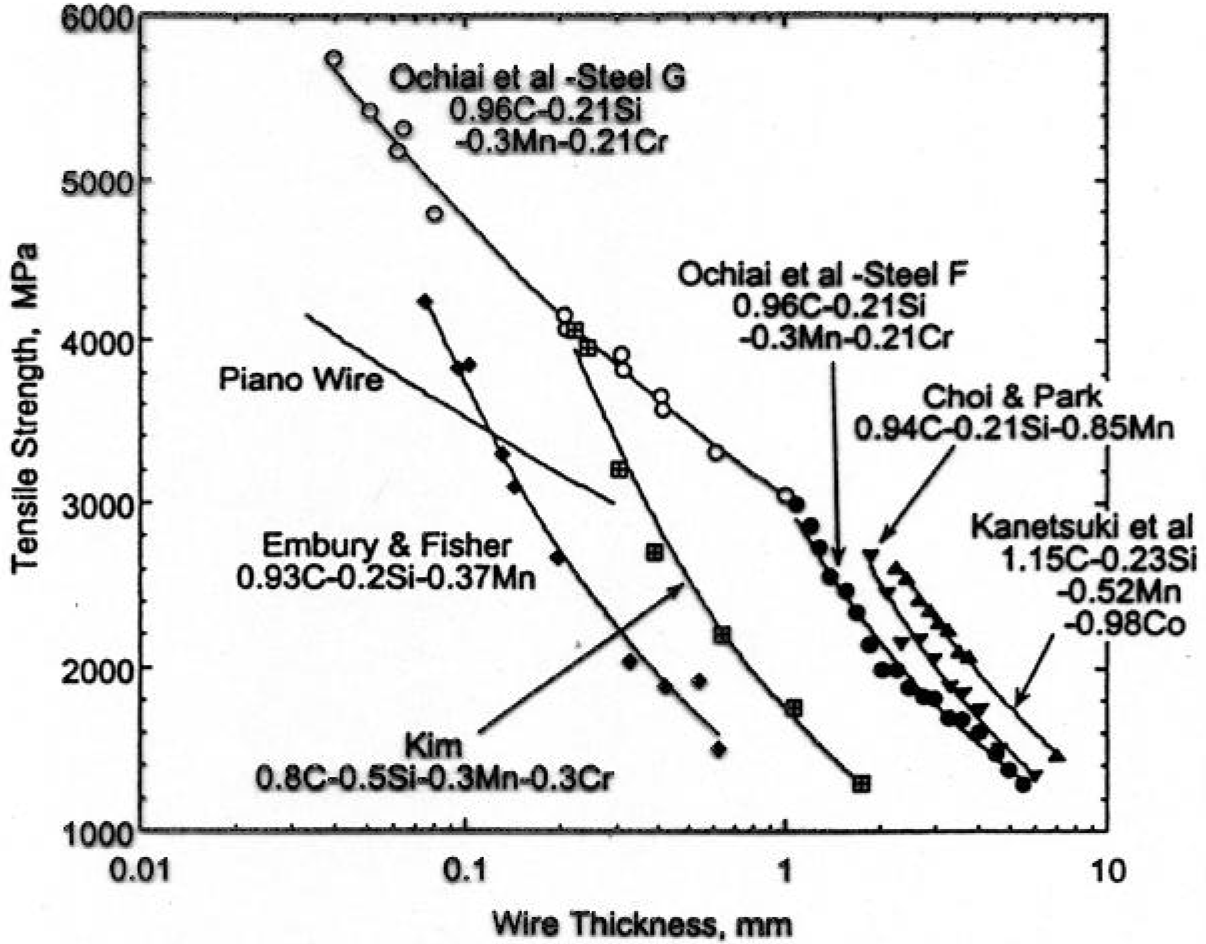
Valiev R.Z.

Grain boundary energy

- Low energy ($\gamma_b < 0.1 - 0.2\,\gamma_0$) – amorphous/crystalline interface, special boundaries.

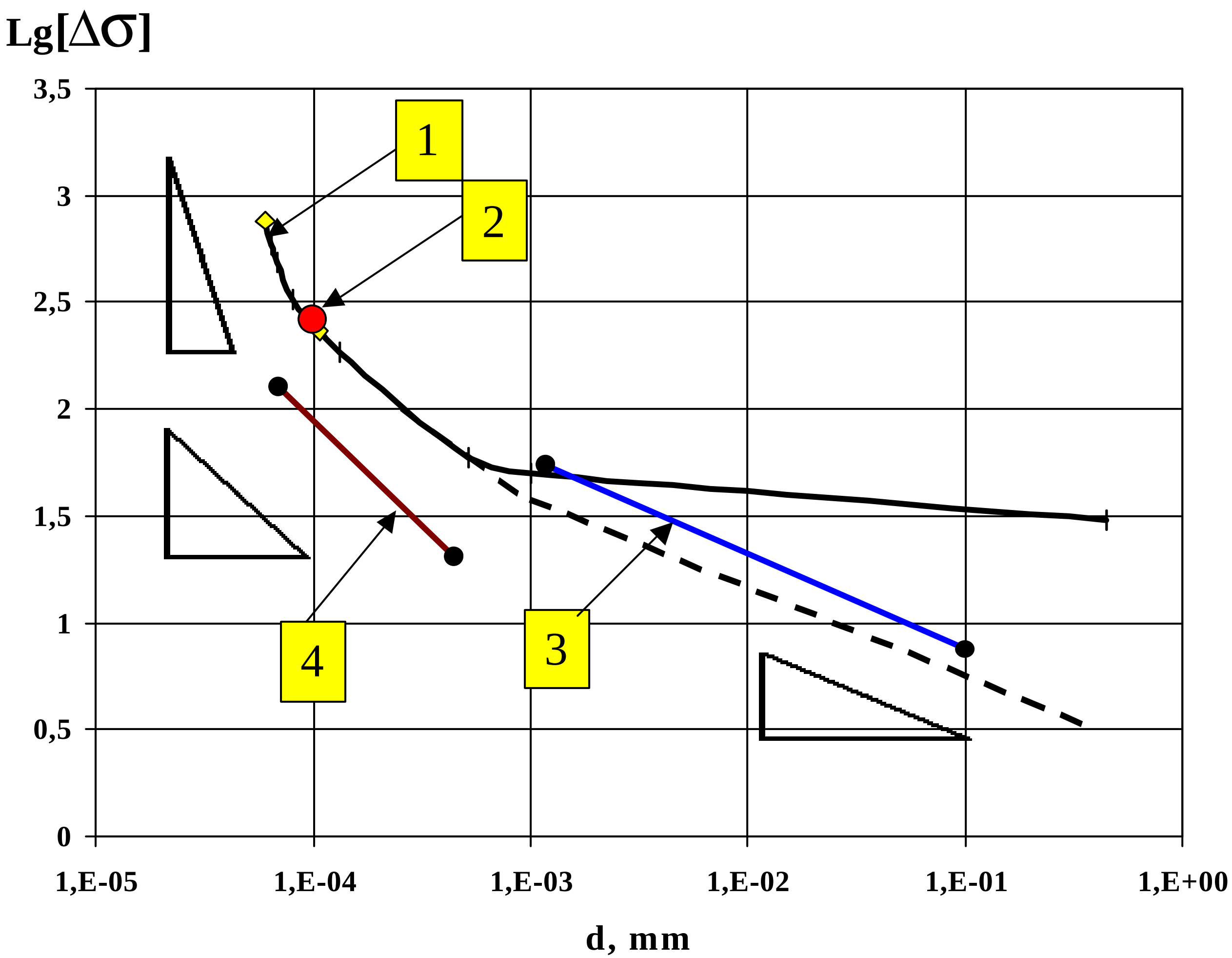
- Middle energy ($\gamma_b < 1/3\ \gamma_0$) – ordered boundaries with random misorientation .

- High energy ($\gamma_b \rightarrow 2\gamma_0$) – non-equilibrium boundaries with disordered structure (boundaries produced during low temperature deformation).



Tensile strength as a function of wire diameter during wire drawing for eutectoid and hypereutectoid steels

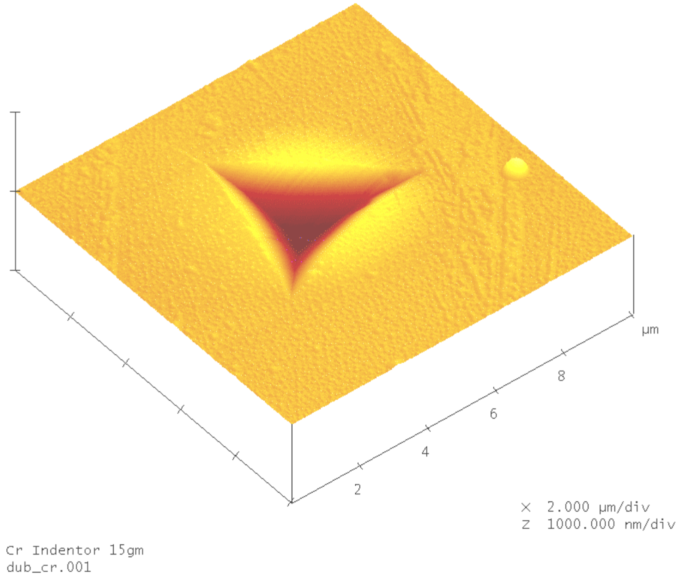
Chromium coatings produced by magnetron sputtering



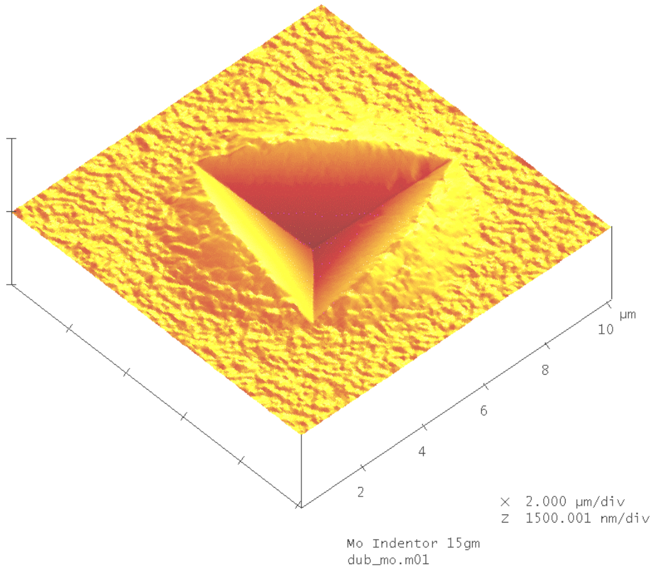
1 - magnetron sputtering of Cr coatings;
2 - ion-plasmic Cr coatings;
3 - (Fe-C);
4 - (Fe-0,49%Ti)

Chromium coating produced by magnetron sputtering (t=400nm)

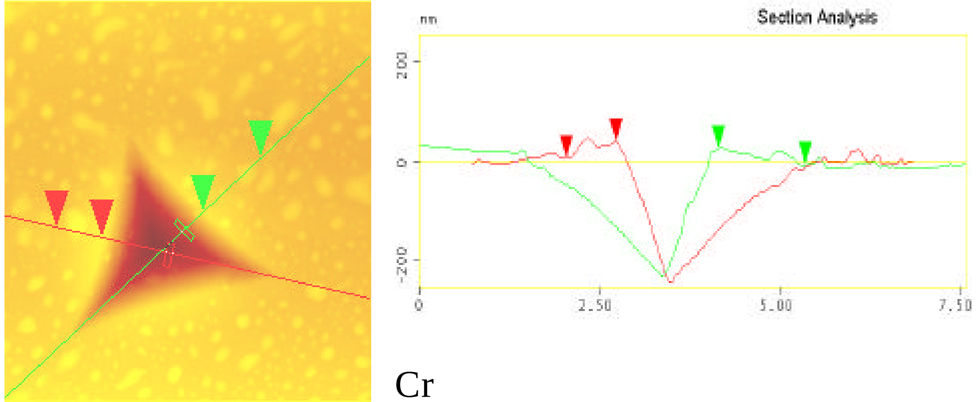
AFM image of indentation made in the chromium and molybdenum produced by magnetron sputtering on silicon substrates



Cr

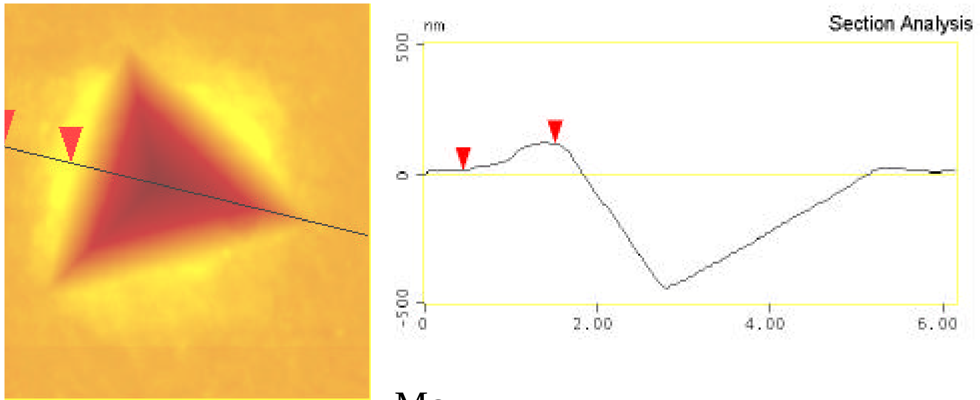


Mo



Cr

Indentor 5gm



Mo

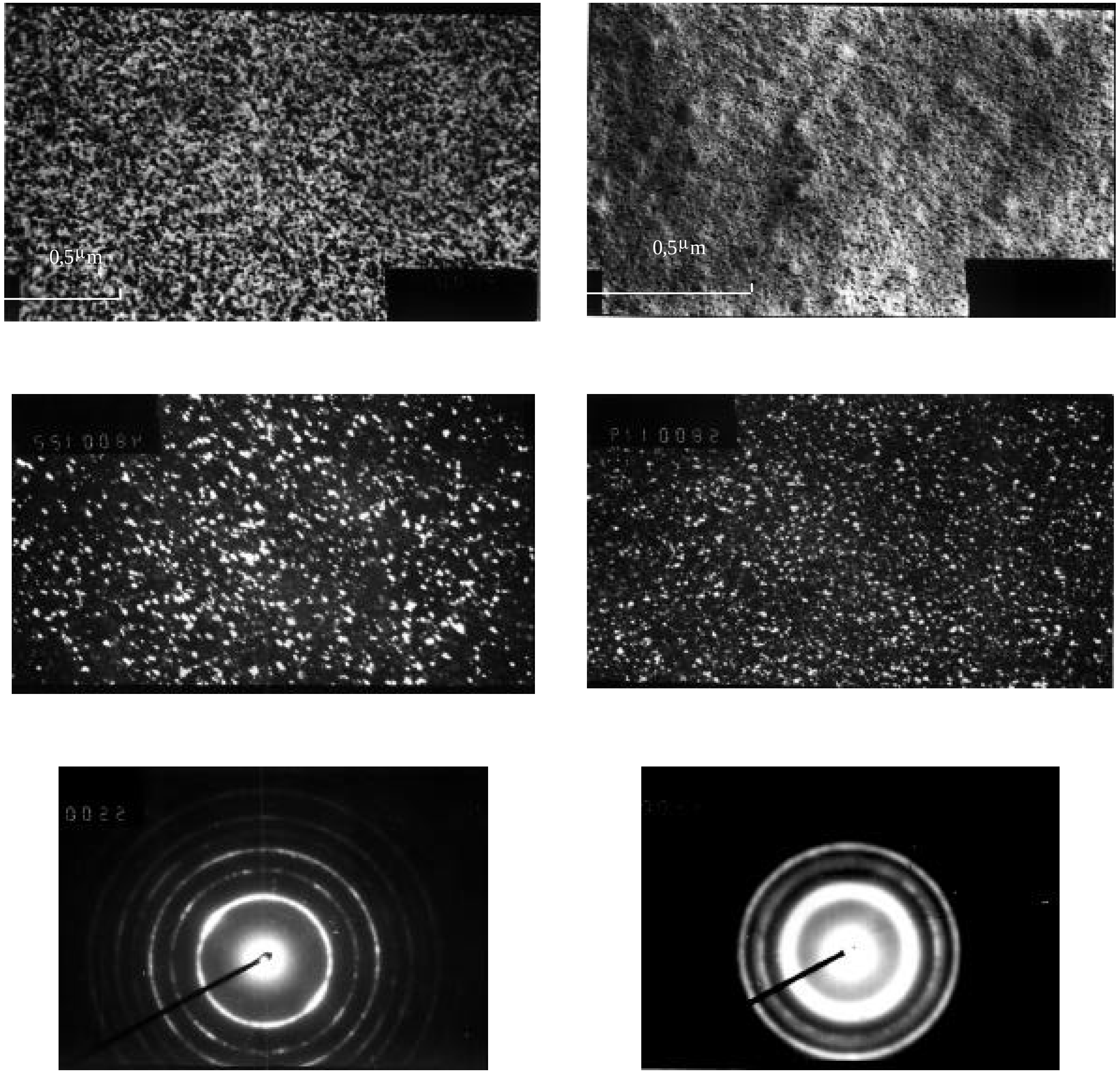
Indentor 5gm

Cross-section of indentation in the chromium and molybdenum produced by magnetron sputtering on silicon substrates

(AFM)

	Load, gm	Indentation depth, nm	Height of the pile-up, nm
Cr	5	235,69	33
Cr	15	409,3	98,7
Mo	5	377	104
Mo	15	661	198

Cr Mo



Chromium and molybdenum produced by magnetron sputtering

Boundary

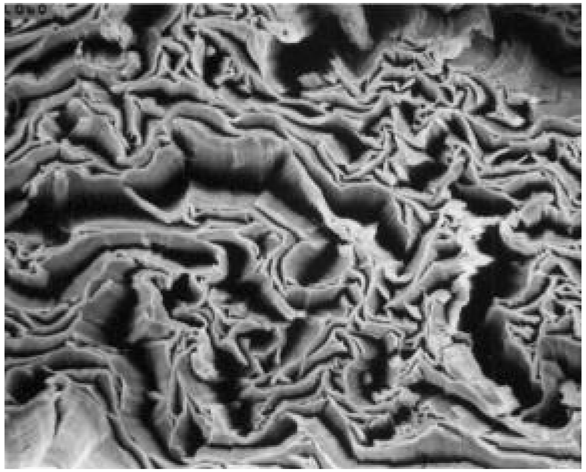
M-M-M-M=M-M-M-M
M-M-M-M=M-M-M-M
M-M-M-M=M-M-M-M
M-M-M-M=M-M-M-M
M-M-M-M=M-M-M-M
M-M-M-M=M-M-M-M

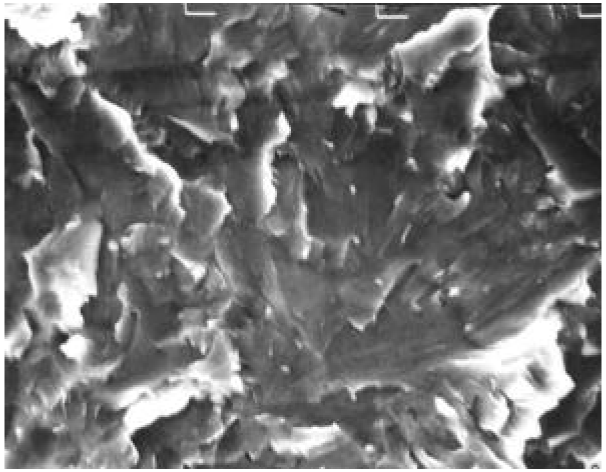
M-M-M-M=M-M-M-M
M-M-M-M=X-M-M-M
M-M-M-X=M-M-M-M
M-M-M-M=X-M-M-M
M-M-M-X=X-M-M-M
M-M-M-M=M-M-M-M

If E_{xx} > E_{MM} and E_{MX}>E_{MM} strength (hardness) increases.

If E_{xx} (E_{MX})< E_{MM} strength (hardness) decreases.

FRACTURE SURFACES OF HEAVILY DEFORMED Cr AND Mo





	$-^{D}H_{298}$		T melting, K
	Kilojoules/mole	Kilocalorie/mole	
Cr	397.75	95.0	2173
Cr_2O_3	1130.4	270.0	2538
Mo	659.42	157.5	2883
MoO_2	548	131	2200

"Useful" impurities (additives) concept

Theoretical strength can be achieved at d≈0.02 μm. Practically, in one-component systems, the "negative" Hall-Petch (or strength saturation) has been observed in many investigations at the nanoscale level of grain sizes. The main reason for such phenomenon is the increase of the "bad" material volume in nanostructured materials with decreasing the grain size.

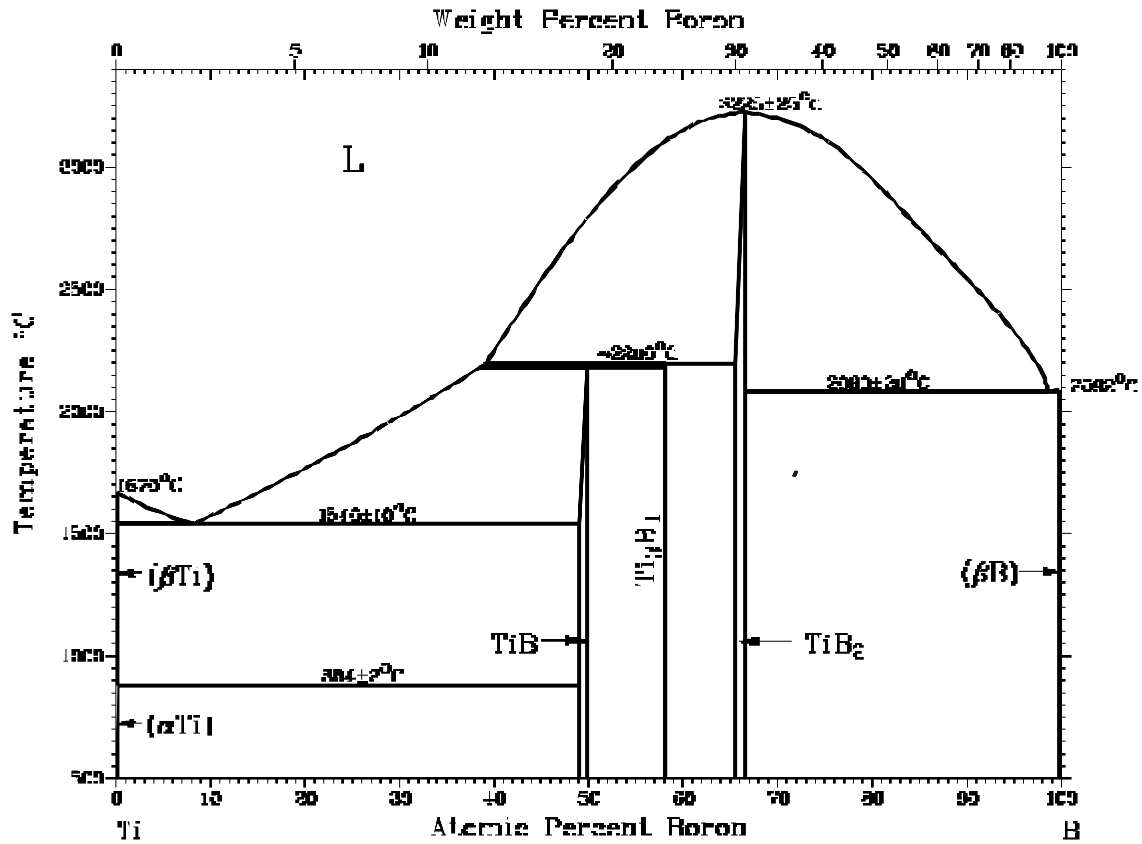
In multicomponent systems the possible **healing of the week points** in the grain boundaries structure can occur and this can lead to the extremely high strength (hardness). Using the **segregation of the useful impurities** or alloying elements, it is possible to realize the healing of weak places in the grain boundaries and to obtain the essential increase of mechanical properties as a result.

PART 2

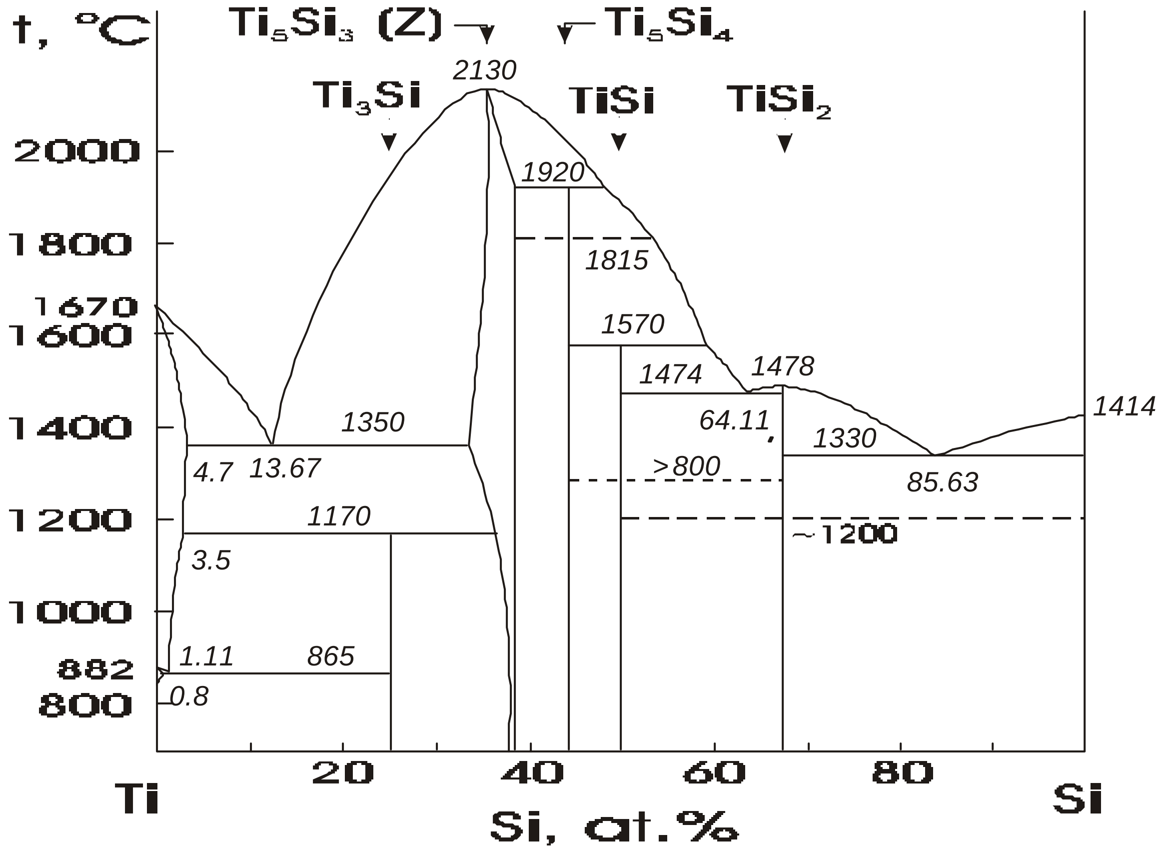
Advanced Ti – based materials

Properties of Ti alloys and Discontinuously-Reinforced Ti (DRTi) materials

	Ti-6Al-4V	Ti-6Al-4V + 3% TiB	Ticompl. alloyed + 5% TiB	Ti-6Al-4V +10(20)% (TiB+TiC)	TENTATIVE GOAL	ACHIEVED Ti-9.0Al-2.2Zr-1.6Si deformed
Modulus (GPa)	110-115	125	132	141/168	≥150%of matrix = 170	~135-140
YS (MPa)	840-1070	1007	1175	1406/ 1181	≥140% of matrix = 1400	-
UTS (MPa)	940-1180			1550/ 1215	≥140% of matrix = 1500	b 1180 a 1230
Strain (%)	7-20%	9.5	5.0	4.6/0.6	≥5%	b 0.8 – 1.6 a 3.8 – 6.1
K_{IC} (MPa.√m)	44-66 (α+β) 88-110 (β)	47			≥30	b 19.2 a 51.1
Max Oper. Temp	427°C (800°F)				≥600°C (~1100°F)	at 700 °C b 650 at 700 °C a 400

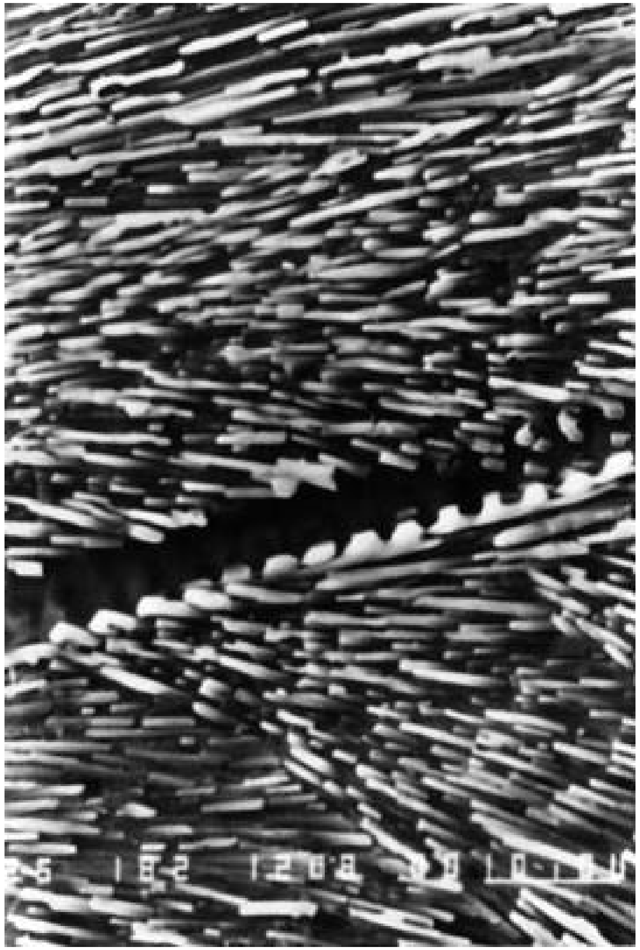


The Ti-B system from Massalski's handbook.

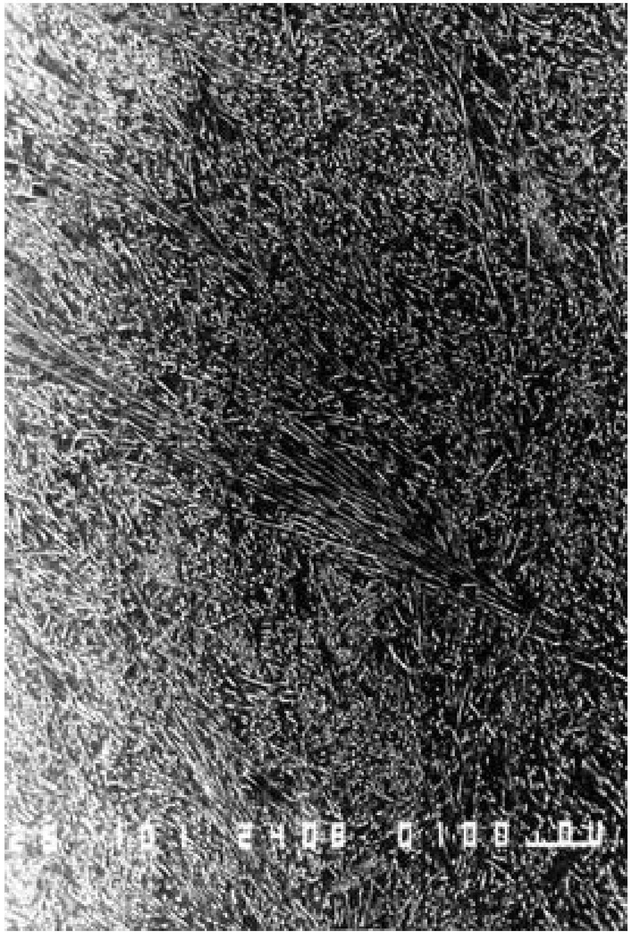


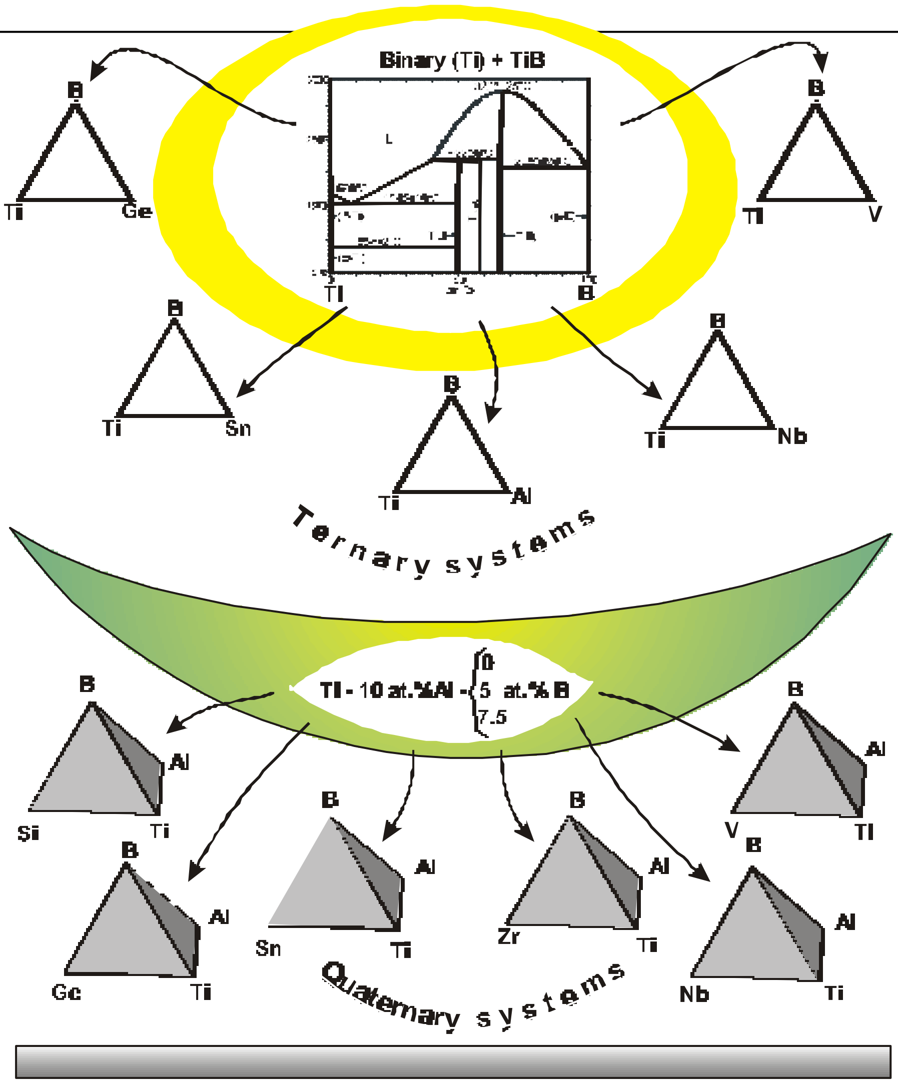
The Ti-Si system, Dr. Bulsnova's assessment.

Ti -8,5 Si (wt. %), DEEP ETCHING, SEM. UPERPROBE -733



Ti – 2.0 B (wt. %), STRUCTURE, SS

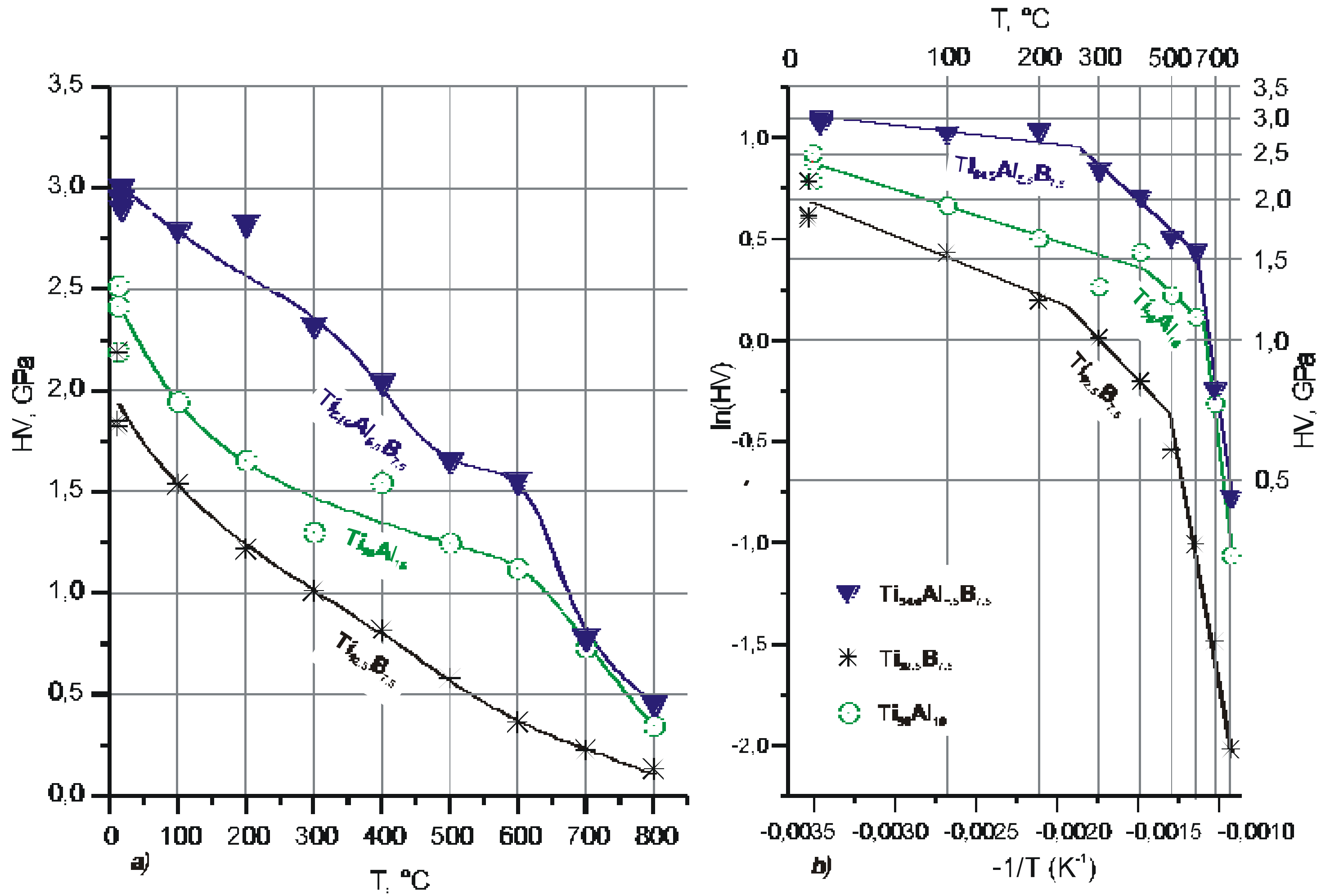




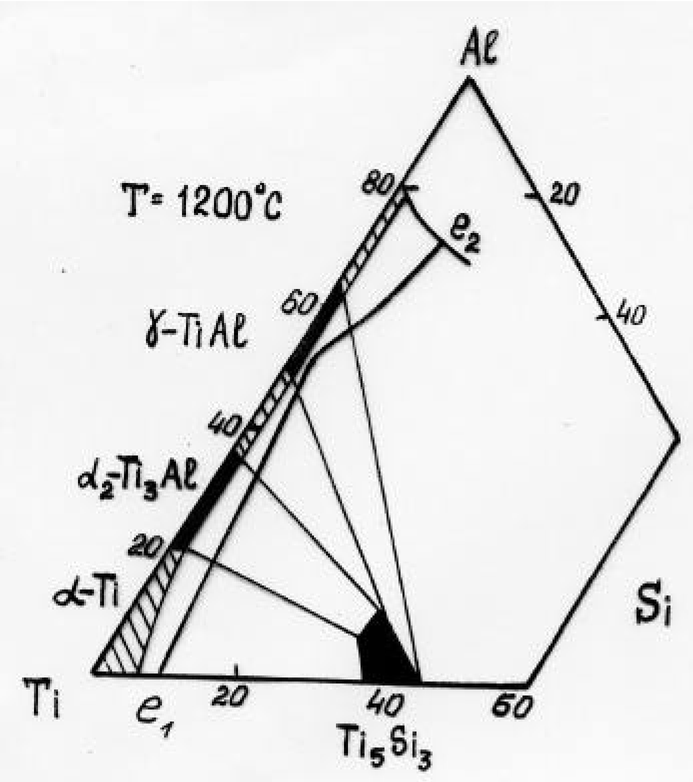
Multicomponent alloys:

Ti-Al-Ge-Sn-(0;5;7.5)B; Ti-Al-Ge-Sn-Zr-(0;5;7.5)B;
Ti1100 + (TiB); IM I834 + (TiB)

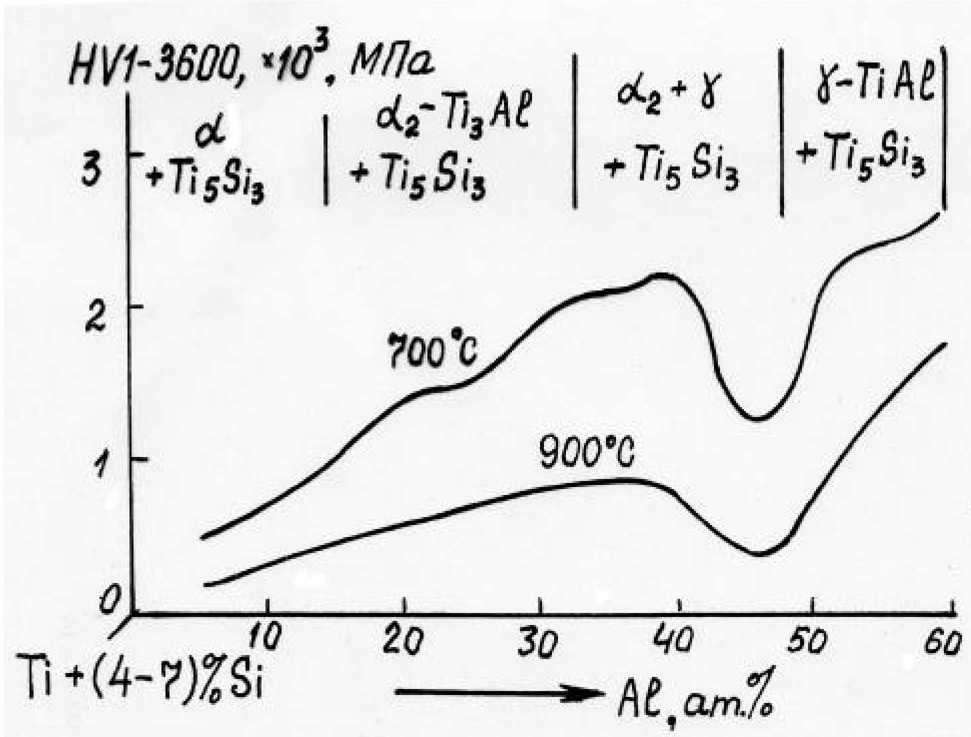
Strategy of research work on alloying of the binary (Ti) + TiB eutectic alloy.



Contributions of alloying additives to the hardness of $Ti_{88}Al_{5}B_{7.5}$ alloy compared with the appropriate binaries, HV vs T (*a*) and *lg(HV)* vs *-(1/T* (*b*).

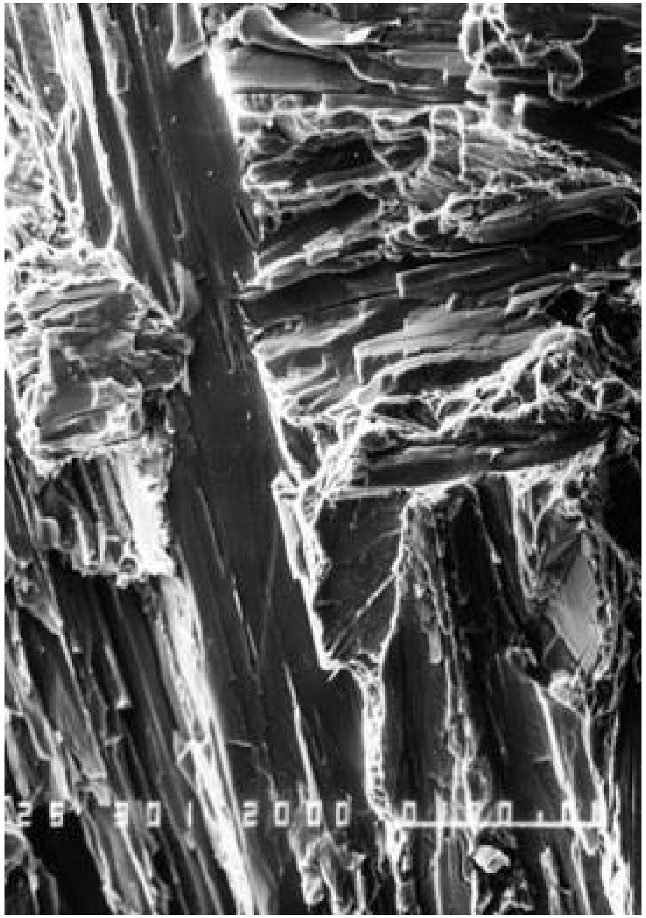


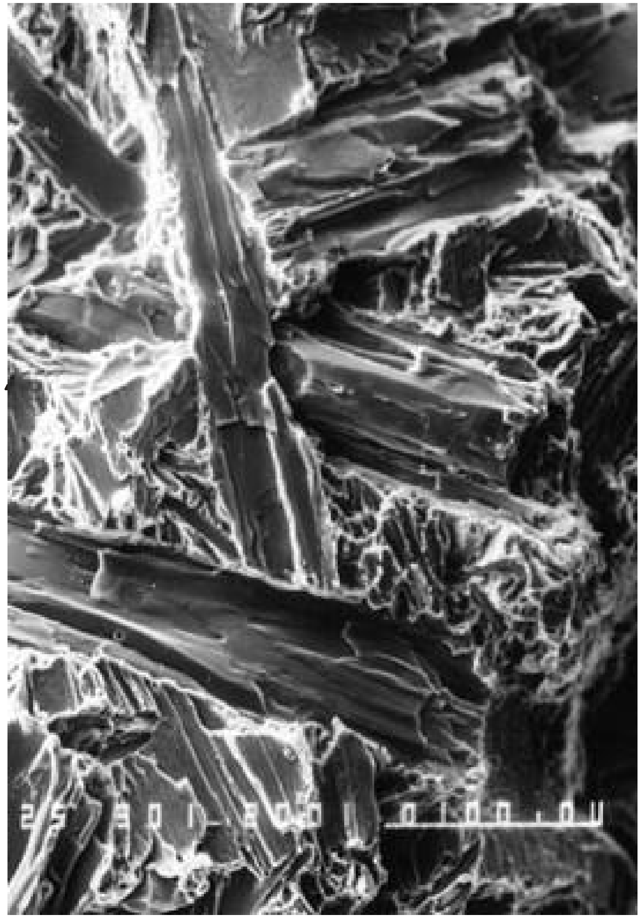
Al
T = 1200°C
80
20
40
60
e2
γ-TiAl
α2-Ti3Al
α-Ti
Si
Ti
e1
Ti5Si3



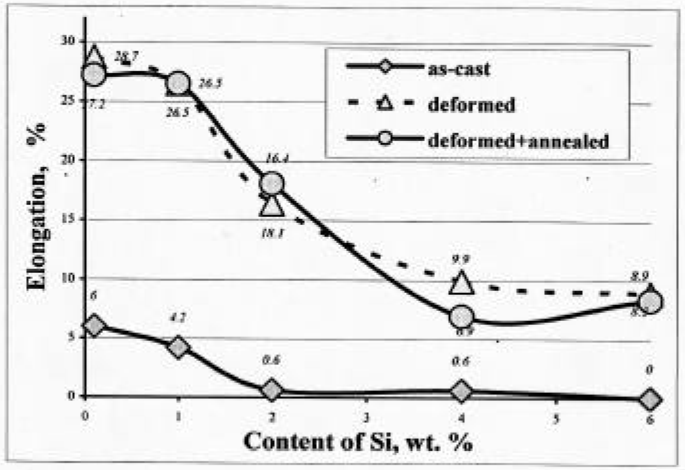
HV1-3600, ×10³, МПа
α + Ti5Si3
α2-Ti3Al + Ti5Si3
α2 + γ + Ti5Si3
γ-TiAl + Ti5Si3
700°C
900°C
0
1
2
3
10
20
30
40
50
60
Ti + (4-7)%Si
Al, at.%

FRACTURE MICROMECHANISMS OF AS-CAST Ti – 3.5 B, iod, 20^{0}C

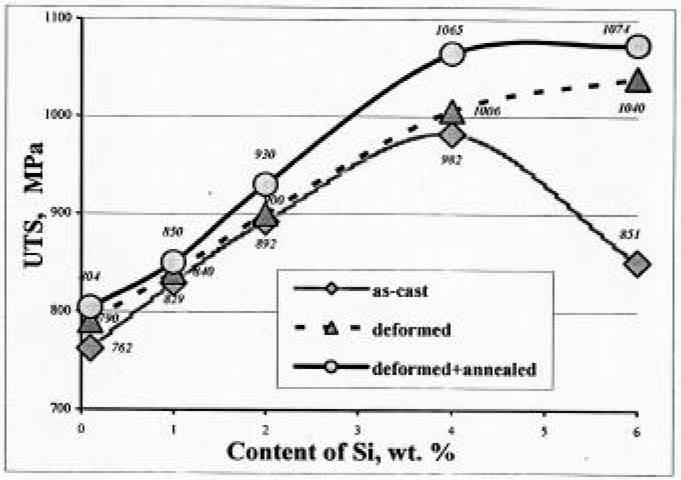


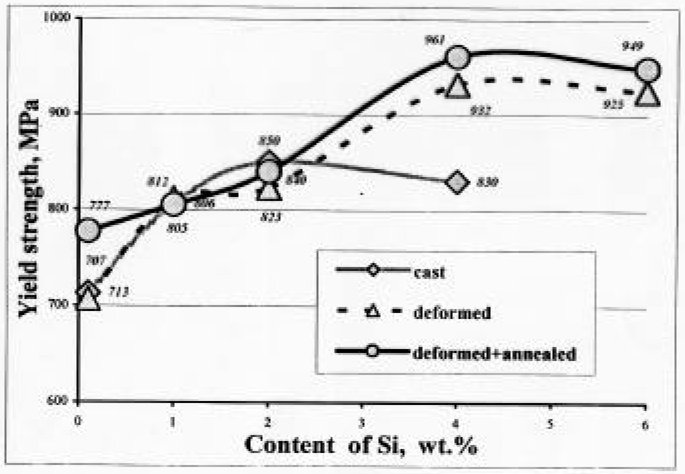


Binary Ti – Si system



Ultimate tensile strength (UTS), yield strength and plasticity (elongation, δ) of commercial titanium alloy BT1-0 vs. silicon content in it for as-cast, deformed (forged for 90 %) and forged + annealed at 800 °C for 2 hours states.





Properties of selected alloys after forging, ε > 60%

<table>
<tr><th>Alloy</th><th>RT strength, UTS, MPa</th><th>RT fracture toughness K_{1c}, MPa $m^{1/2}$</th><th>RT yield strength, $\sigma_{0.2}$ MPa;</th><th>RT elongation, δ%;</th><th>RT fracture micro-mechanism</th><th>Elasticity modulus, GPa</th></tr>
<tr><td rowspan="2">Ti-6.3Al-5Zr-1.8Si LM-863</td><td>1220</td><td></td><td>1120</td><td>5.4</td><td rowspan="2">void coales-cence</td><td></td></tr>
<tr><td colspan="4">in process</td><td></td></tr>
<tr><td rowspan="2">Ti-6.6Al-3.5Zr-1.3Si-1.1B LM-908</td><td>1530</td><td></td><td>1469</td><td>1.4</td><td rowspan="2">void coales-cence</td><td>158</td></tr>
<tr><td colspan="4">in process</td><td></td></tr>
<tr><td rowspan="2">Ti-9.0Al-2.2Zr-1.6Si LM-905</td><td>1302</td><td></td><td></td><td>1.83</td><td rowspan="2">void coales-cence</td><td>~140</td></tr>
<tr><td>β 1180
α 1230</td><td>β 19.2
α 51.1</td><td></td><td>β 0.8 – 1.6
α 3.8 – 6.1</td><td></td></tr>
<tr><td rowspan="2">Ti-5.5Al-1.9B LM-903</td><td>1184</td><td></td><td>1140</td><td>6.24</td><td rowspan="2">void coales-cence</td><td>152</td></tr>
<tr><td colspan="4">in process</td><td></td></tr>
</table>

Structure of as–cast (a) and as– forged (b) Ti – Al – Zr – Si - B

a X 400 SEI

b X 400 SEI

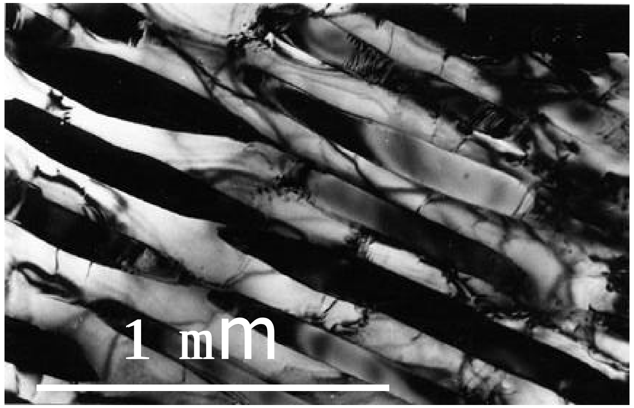
Ternary Ti-B system

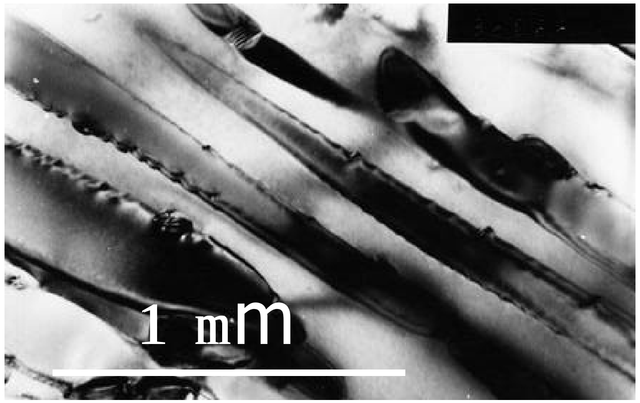
Tensile yield strength ($\sigma_{0.2}$), ultimate tensile strength (UTS), plasticity (elongation,δ) and elasticity modulus (E) of complex alloyed Ti-B alloys, deformed and annealed (800°C, 2 hours), at room temperature. Produced with arc (AM) and electron beam melting (EBM) of BTI-O alloy.

Chemical composition	Melting	As-cast			Forged			
		UTS, MPa	$\sigma_{0.2}$, MPa	δ, %	UTS, MPa	$\sigma_{0.2}$, MPa	δ, %	E, GPa
Ti-3Al-1.2B (2B-57)	AM	1020	1000	1,2	1033	972	7.2	137-138
Ti-5.5Al -1.9B (LM-903) annealed 800 °C	EBM	-	-	-	1184	1140	6.24	151-152

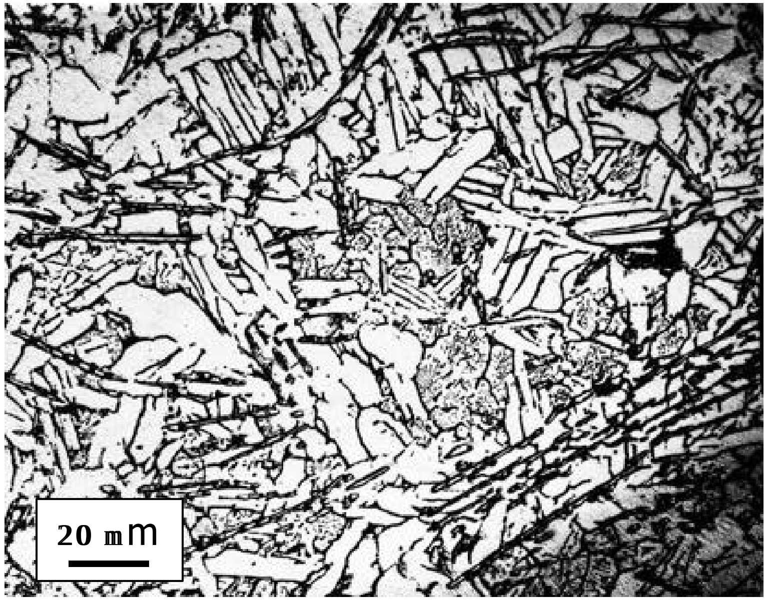
Ti – Al – Si – B

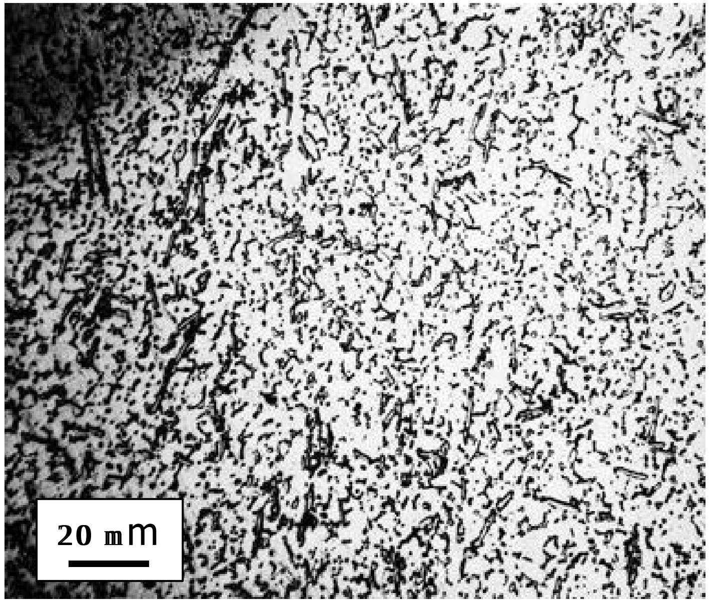
Ti – Si – B





Structure of as–cast and as–rolled alloys
Ti – 4Al – 4Zr – 1Si – 2B





CONCLUSIONS

The following directions of R&D in the field of elaboration of materials with high specific strength are actual:

1. Further elaboration of different methods producing of nanostructured materials including gradient nanostructured materials
2. Grain boundary engineering of nanostructured materials including thermo-chemical treatment based on concept of "useful" additives
3. Clarifying of the mechanisms of plasticity in nanostructures. Achievement of a good combination of different mechanical properties (σ, δ, ψ, K_{1c} , fatigue properties, heat resistance etc.)
4. Phase equilibria investigations of multicomponent systems as base for producing of advanced materials strengthened by quasicrystals, intermetallics, creation in situ composites, nanocomposites, nanolaminates, amorphous structures etc.
5. Further development lightweight materials including porous materials with different volume and morphology of pores

As to Ti-based materials:

1. Ti-Si-X systems alloys are attractive for creation of heat resistant materials
2. Ti-B-X systems alloys are promising for achievement of high specific stiffness
3. Further investigations of Ti-B-Si-X alloys. Amorphisation, icosahedral phase production, search of new strengthening phases
4. Methods of obtaining of alloys with high boron content
5. Ti-Si-X systems alloys are a good matrix for producing MMM's